Splitting electronic spins with a Kondo double dot device

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(Dated: February 2, 2008)

We present a simple de made of two small capacitively coupled quantum dots in parallel. This set-up can be used as an efficient "Stern-Gerlach" spin filter, able to simultaneously produce, from a normal metallic lead, two oppositely spin-polarized currents when submitted to a local magnetic field. This proposal is based on the realization of a Kondo effect where spin and orbital degrees of freedom are entangled, allowing a spatial separation between the two spin polarized currents. In the low temperature Kondo regime, the efficiency is very high and the de conductance reaches the unitary limit, $\frac{e^2}{h}$ per spin branch.

PACS numbers: 72.15.Qm, 85.35.Gv, 85.75.-d

Controlling the electron spin in electronic circuits is the challenge of the new emerging field called spintronics. Part of current research aims at the injection of spin-polarized electrons into mesoscopic structures. For instance, control of single spins, owing to long decoherence times in semiconductor nanostructures, opens the way to spin-based quantum information processing. [1] One of the major goals is the production of efficient spin filters, with the following requirements : i) high polarization, especially for very demanding tests of quantum entanglement [2]; ii) bidirectional spin filtering, e.g. filtering at will "up" and "down" spins; iii) low impedance, to allow unperturbed transport (conductance and noise) measurements on a variety of de s. Several set-ups fulfilling part, but not all the above constraints, have been proposed or tested to inject spins or create spin filters. They rely either on ferromagnetic materials [3], external magnetic fields [4, 5, 6, 7], or spin-orbit coupling. [8] Recher *et al.* [4] have in particular considered a quantum dot weakly coupled to current leads, in the sequential tunneling regime. They have shown that in the presence of a local magnetic field it can act as an efficient spin filter whose spin direction can be controlled by energy filtering, with the help of the dot plunger gate voltage : given a single electron level in the dot, with occupancy n, transitions between $n = 0, 1$ states or between $n = 1, 2$ states respectively involve opposite spins. Another interesting possibility developed by Borda *et al.*[6] is to use a double quantum dot (DD) system with strong capacitive interdot coupling. When an external magnetic field is applied to such a system, these authors showed that the low energy physics can be described by a purely orbital Kondo effect where spin flip processes are suppressed and only charge fluctuations are allowed between the dots (the latter representing the orbital degrees of freedom). A major consequence of the Kondo effect is the reach of the unitary limit at $T \ll T_K$ where T_K is the Kondo temperature.[9] In this limit the DD proposed by Borda *et al.*[6] thereby acts as an almost perfect unidirectional spin filter (with high conductance e^2/h), provided the temperature is low enough.

In this Letter, we go one step further and propose a simple, robust and efficient "Stern-Gerlach" spin splitter, able to simultaneously produce from a normal metallic lead two oppositely spin-polarized currents, using non-magnetic semiconductor materials. Realization of such a spin splitter, used as a source or an analyzer of polarized electrons, opens the way to many experiments, including Bell correlations of entangled states, [2] or spin-resolved shot noise measurements. [10] Our proposal is schematized in Figure 1. Spin filtering is achieved by energy filtering, as in Ref. 4, selecting each of the spin directions in either dot 1 or 2. Our set-up does not work in the sequential regime, but in the Kondo regime, as in Ref. 6, the two small quantum dots being strongly coupled in a capacitive way. Rather than coupling each dot to two independent reservoirs, here each dot is connected to a common source kept at the chemical potential μ_L and to a distinct current lead at chemical potential μ_R. The two outgoing spin-polarized currents of opposite polarizations emerge from these two separate leads.

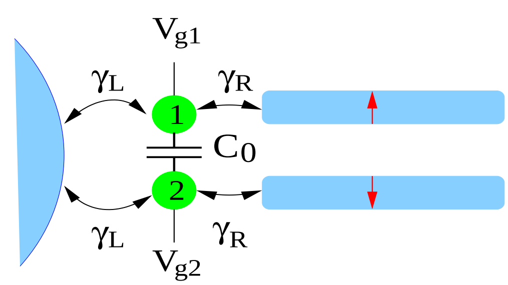

FIG. 1: Schematic representation of the proposed setup: two small quantum dots coupled by a capacity C_0 and connected to a common source. Each dot 1 and 2 is also connected to an extra lead from which the two spin polarized currents will emerge. Depending on how the gate voltages are tuned, the upper lead can be polarized in the up direction and the lower lead in the opposite direction or vice versa.

The numbers of electrons in the dots are controlled by two plunger gate voltages at potential V_{g1} and V_{g2}. We label the lowest-lying charging states by the numbers (n_1, n_2) of extra electron in dots $1, 2$. We consider the regime where the gate voltages are adjusted such as the two lowest-lying and almost degenerate charging states are $(1, 1)$ and $(0, 2)$, instead of states $(1, 0)$ and $(0, 1)$ as in Ref. [6]. A schematic stability diagram is depicted in Fig. 2 showing the different possible charging states. At energies lower than the charging energy of

the dot $E_C = min(E(0,1) - E(1,1); E(1,2) - E(1,1))$, the charge dynamics is restricted to states $(1,1)$ and $(0,2)$, states $(0,1)$ and $(1,2)$ appearing only as virtual states. Let us label the capacitances (choosen symmetric in the dot indices for simplicity) as C_L (left), C_R (right), C_g, C_0 (coupling the two dots), define $C = C_L + C_R + C_g$, and the external charges $C_g V_{g1}$, $C_g V_{g2}$ from a reference state with even occupation numbers. Then the intradot and interdot charging energies are respectively $U = \frac{e^2(C+C_0)}{2C(C+2C_0)}$ and $V = xU$ with $x = \frac{C_0}{C+C_0}$. The condition for degeneracy reads $V_{g2} = V_{g1} + \frac{e}{C_g}$, and the excitation energies are $E(0,1) - E(1,1) = U[(1+x)\frac{C_g V_{g1}}{e} - \frac{1}{2}]$, $E(1,2) - E(1,1) = U[\frac{1}{2} + x - (1+x)\frac{C_g V_{g1}}{e}]$. The optimum regime is reached at the symmetric point O (corresponding to the thick black dot in Fig. 2) where the two excitation energies are equal to $E_c = U\frac{x}{2}$.

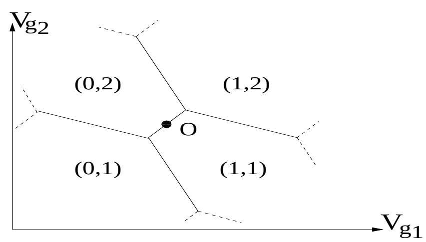

FIG. 2: Sketch of the operation region in the stability diagram showing stable charge states as function of gate voltages V_{g1} and V_{g2}. The thick black dot O corresponds to the ideal operating point in the middle of the degeneracy line.

The isolated DD system is described[6] at low energy by

$$H_{dot} = -\delta E T^z - tT^x - g\mu_B B S^z, \tag{1}$$

where we have defined the orbital pseudospin $T^z = (n_1 - n_2 + 1)/2 = \pm 1/2$. Here $\delta E = E(0,2) - E(1,1)$ is zero when the two lowest-lying charge states are exactly degenerate. The second term in Eq. (1) represents a direct tunneling amplitude between the dots and the last term expresses the Zeeman splitting when a local magnetic field is applied in the z direction.

In the following we assume that the Zeeman energy is large enough such that spin-flip scattering is suppressed. An evaluation of the typical value of the required magnetic field and other experimental parameters is provided at the end of the Letter. The spin states of the two degenerate ground states are therefore $(\uparrow,\uparrow)$ and $(0,s)$ where s stands for singlet state. Triplet states $(0,t)$ can be discarded if the level splitting $\delta\varepsilon$ in each dot is large enough. [4, 5] Defining the total spin operator by $S^z = S_1^z + S_2^z$, it is crucial that $T^z = S^z - \frac{1}{2}$. This means that the spin of the electron added to the "empty" state $(0,\uparrow)$ is entangled with the orbital pseudo-spin:[11] virtual charge fluctuations on dot 1 (resp. 2) involve spin-up (resp. spin-down) electrons exclusively, and an orbital pseudo-spin flip (between states $(\uparrow,\uparrow)$ and $(0,s)$) is locked to a genuine spin flip. Therefore the Kondo screening of the spin involves spin-up electrons in the upper right lead and spin-down electrons in the lower right one, as well as spin-up and spin-down electrons altogether in the common left lead. This is contrary to the set-up of Borda *et al.*,[6] where the real spin is quenched by the applied magnetic field and only the orbital pseudo-spin survives. This is a crucial difference which makes possible the realization of a spin splitter from our proposal. Before turning to a more quantitative analysis, we also emphasize that the tunneling term, being spin independent, no longer connects the two degenerate states, as opposed to the situation occurring in [6]. We can therefore neglect it provided $t << g\mu_B B$. In practice, this makes a strong capacitive coupling between the dots easier to achieve than in Ref. 6 where $t << T_K$ is instead required.

The leads are described by $H_{\text{leads}} = \sum_{k,\alpha,\sigma} \varepsilon_k c^\dagger_{k,\alpha,\sigma} c_{k,\alpha,\sigma}$, where $c^\dagger_{k,\alpha,\sigma}$ creates an electron with energy ε_k in the lead α and spin σ. Indeed, Zeeman splitting in the reservoirs can be made much smaller than in the dots. [4] Since the Coulomb energy E_C is one of the largest energy scales, only cotunneling processes where the numbers of initial and final electrons in the DD are equal are allowed. Therefore we need only to consider virtual excitations towards states with $n_1 + n_2 = 1$ and 3 in the DD. Using second-order perturbation theory in the tunneling amplitude between the dots and the leads, we obtain a Kondo effective Hamiltonian $H_{eff} = H_K + H_{tun}$ with

$$\begin{aligned} H_K \;=\; & \sum_{k,k',\alpha,\beta} \Big[J_{k,k',\alpha,\beta} (c^\dagger_{k,\alpha,\downarrow} T^+ c_{k',\beta,\uparrow} + h.c.) \Big] \\ & + \sum_{k,k',\alpha,\beta} \Big[J_{k,k',\alpha,\beta} T^z (c^\dagger_{k,\alpha,\uparrow} c_{k',\beta,\uparrow} - c^\dagger_{k,\alpha,\downarrow} c_{k',\beta,\downarrow}) \Big] \end{aligned} \tag{2}$$

the Kondo part involving the flip of the pseudo-spin $\vec{T}$ and

$$H_{tun} = \sum_{k,k',\alpha,\beta,\sigma} \Big[V_{k,k',\alpha,\beta} (c^\dagger_{k,\alpha,\sigma} c_{k',\beta,\sigma} + h.c.) \Big] \tag{3}$$

corresponds to tunneling between the leads. In these expressions the lead index α,β takes only the two values L, R. Due to spin-orbital entanglement, the distinction between the two right leads is simply given by the spin index: $(R,\uparrow)$ corresponds to the upper right lead and $(R,\downarrow)$ to the lower right lead. The coupling V being spin independent, there is no tunneling between the two right leads. As usual we can neglect the k dependence of the Kondo couplings i.e. $J_{k,k',\alpha,\beta} \approx J_{\alpha,\beta} \sim \sqrt{\gamma_\alpha \gamma_\beta}/E_C$ and $V_{k,k',\alpha,\beta} \sim J_{\alpha,\beta}/4$, with γ_α the tunneling rate from/to lead α. There are other cotunneling terms with smaller amplitudes involving for example higher energy processes like $E_C(2,1) - E_C(1,1) \gg E_C$. These terms may a priori pollute spin filtering. Nevertheless the strength of the Kondo effect is to renormalize the Kondo couplings toward strong coupling at low energy as opposed to direct potential scattering terms that do not renormalize. Therefore terms like those involved in Eq. (3) or other higher energy potential scattering terms can be dropped out in the low temperature regime $T \ll T_K = D\exp[-1/\rho_0(J_{LL} + J_{RR})]$, where a constant density of states ρ_0 has been assumed in the leads. This corresponds to the unitary limit [9] where the spin and orbital pseudospin are completely screened and a singlet is formed together with spin-up/down electrons in the left lead, spin-up

electrons in the upper right lead and spin-down electrons in the lower right lead.

Transport across the double dot can now be described, applying a small voltage $eV = \mu_L - \mu_R$. The conductance of each right lead is given by $G_{L,R1,\uparrow} = G_0 sin^2\delta_\uparrow$ and $G_{L,R2,\downarrow} = G_0 sin^2\delta_\downarrow$, both tending towards $G_0 = \frac{4\gamma_L\gamma_R}{(\gamma_L+\gamma_R)^2}\frac{e^2}{h}$ for $T << T_K$ where the phase shifts $\delta_\uparrow$, $\delta_\downarrow$ are equal to $\pi/2$. The conductances reach e^2/h at $T = 0$ for symmetric tunneling amplitudes. Notice that in the unitary limit, the polarization of the currents in the right leads is almost perfect, e.g. $G_{L,R1,\downarrow} = G_{L,R2,\uparrow} \sim 0$.

The ground state in the unitary limit is a Fermi liquid which is usually stable toward various perturbations. Let us analyze them in details. First, δE in (1) plays the role of an orbital magnetic field lifting the degeneracy between the dot 1 and 2 levels. Therefore the two plunger gate voltages V_{g1} and V_{g2} need to be finely tuned such that $\delta E \ll T_K$, in order to reach the unitary limit. In addition, we have assumed from the beginning that the tunneling amplitudes between the dots and their respective right leads are equal. Actually, a different tunneling amplitude would lift the spin degeneracy between electrons with spin up and down, playing a role similar to an effective magnetic field. The situation is also analogous to that of a single quantum dot in the Kondo regime, with ferromagnetic reservoirs breaking the symmetry between up and down spins. In this situation, the spin dissymetry can be compensated by applying a magnetic field. [12, 13] In the present case, one would simply need to correct by slightly modifying the gate voltages V_{g1} or V_{g2} (except [13] at the symmetric point O).

Let us now estimate the experimental requirements to realize our proposal. First, in a large enough magnetic field, the above set-up should exactly map on a single-dot Kondo problem. This requires, as in Ref. [6], that $g\mu_B B > T_K^{(0)}$, which is the Kondo temperature of the system without a magnetic field whose behavior is also expected to be described at low energy by a SU(4) Kondo problem with four (orbital and spin) degenerate states. [6, 11] Note that due to the higher symmetry $T_K^{(0)} \gg T_K$. Then, the main conditions are set by the necessary Zeeman splitting $g\mu_B B$, e. g. $g\mu_B B < \delta\varepsilon$, to avoid populating a triplet state in dot 2, more precisely $\delta\varepsilon - g\mu_B B > T_K$. The working conditions can then be summarized as $T < T_K < T_K^{(0)} < g\mu_B B < \delta\varepsilon, E_C$, and $t < g\mu_B B$. They are consistent with small dots with large magnetic fields, e. g. typically $T_K \sim 0.1K$, $T_K^{(0)} \sim 0.5K$, $B \sim 10T$ with $g = 0.44$, $\delta\varepsilon \sim U \sim V \sim 1meV$. These conditions are comparable to the ones proposed in ref. [6] and an efficiency of around 95% can be reached at low enough temperature $T \ll T_K$.

As a conclusion, we have used an exotic Kondo effect, where spin and orbital degrees of freedom are entangled, to propose a simple, robust and efficient spin splitter. We hope that this proposal will open new opportunities in the field of spintronics based on the application of the Kondo effect in semiconductor quantum dots.

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